Parity Nonconservation and the Standard Model:

The Standard Model of Particle Interactions

Three Generations of Matter

I   II   III

Quarks: u c t   γ
        d s b   g

Leptons: v_e v_μ v_τ Z
         e   μ   τ   W
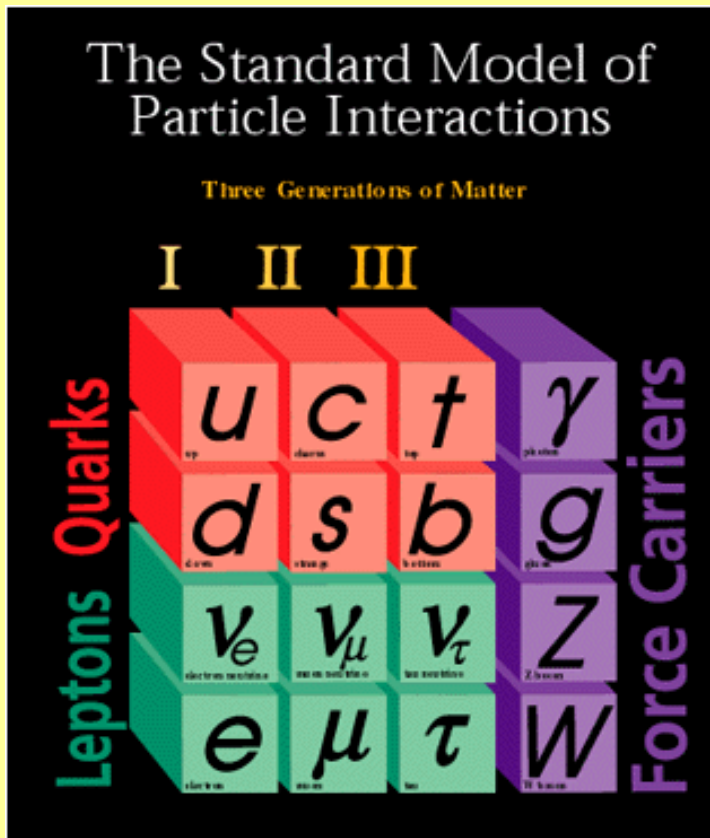
Force Carriers

Weak force carriers, W+, Z°, W- have spin 1 (bosons) and are left-handed, i.e. they have h = -1 always (spin opposite to direction of motion)

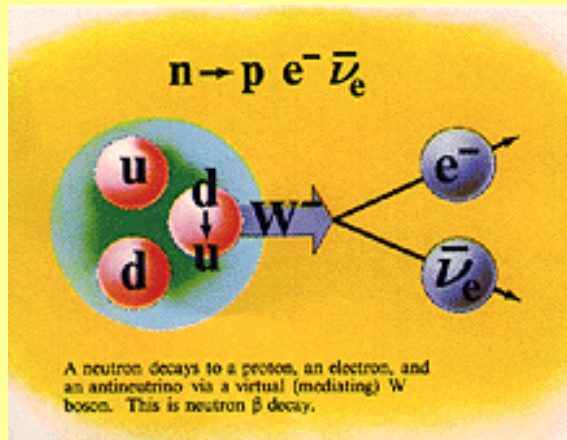If this is the case, then parity violation in the weak interaction is a "built-in" feature.

But nobody knows why....

Extensive searches for physics "Beyond the Standard Model" probe the existence of a symmetric set of right-handed force carriers.

None detected yet, but if they exist, they are required to be extremely heavy!

Neutrinos: v_e etc. have negative helicity;   antineutrinos have positive helicity!

Many precise experimental tests are in agreement with this picture – see the particle data group web page for a current summary.   High energy collider experiments have played a major role in discovering the heavier quarks and members of the lepton family...

$$n \rightarrow p\ e^- \bar{\nu}_e$$

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

The picture of short-range, heavy charged force carriers gives a mechanism for nuclear beta decay that is consistent with older theories and experimental data.

.. but if the W- only travels 0.002 fm at the speed of light, how do we know it is there? ……

The neutral weak force carrier Z^0 is not required to explain beta decay, but is predicted to be a 'heavy cousin' of the photon, and the mediator of 'neutral' weak interactions – something that was not foreseen prior to the development of the current "electroweak" interaction theory by Glashow, Weinberg & Salaam – Nobel prize 1984.
   http://nobelprize.org/physics/laureates/1984/index.html

Immediate consequences: e.g. parity violating (PV) electron scattering, now a standard tool for nuclear and particle physics (e.g. Q_weak experiment: http://www.jlab.org/qweak/)

e

e

Z^0

q

q

e

$\vec{s}(+)$

p
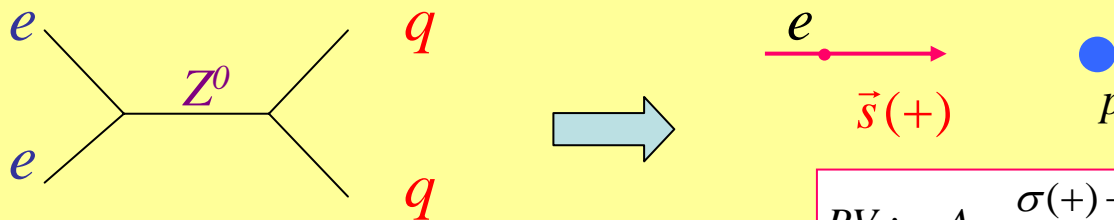
$$PV: \quad A = \frac{\sigma(+) - \sigma(-)}{\sigma(+) + \sigma(-)} \cong -10^{-5}\, Q^2\, (GeV^2) + O(Q^4)$$

Direct evidence: creation of weak force carriers in colliding beam experiments

consider first a fixed-target experiment: extra kinetic energy in the beam is "wasted" rather than used for new particle production, since momentum has to be conserved (forward direction)
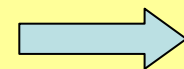
before $\vec{p}$

after

beam, total energy E   fixed target, mass M   new particle, mass M* > M
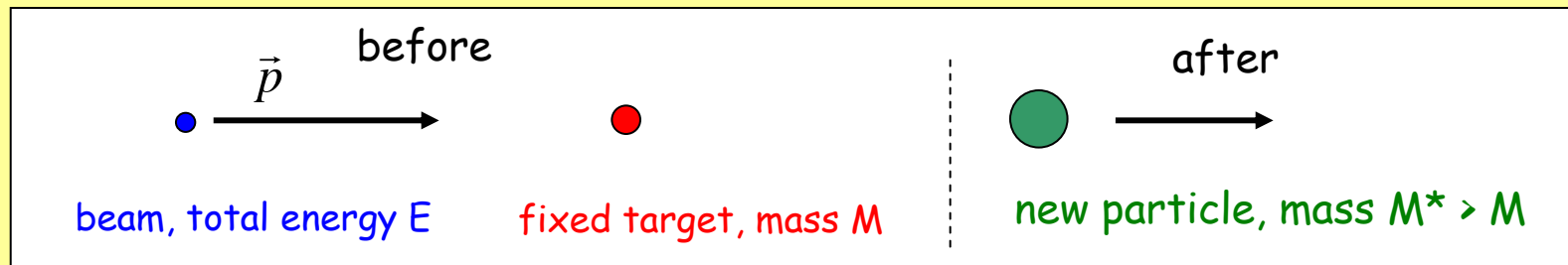
minimum energy to produce M* corresponds to zero kinetic energy in the center of momentum frame:

before

after

total 3 momentum = 0   total energy E* = M* at threshold
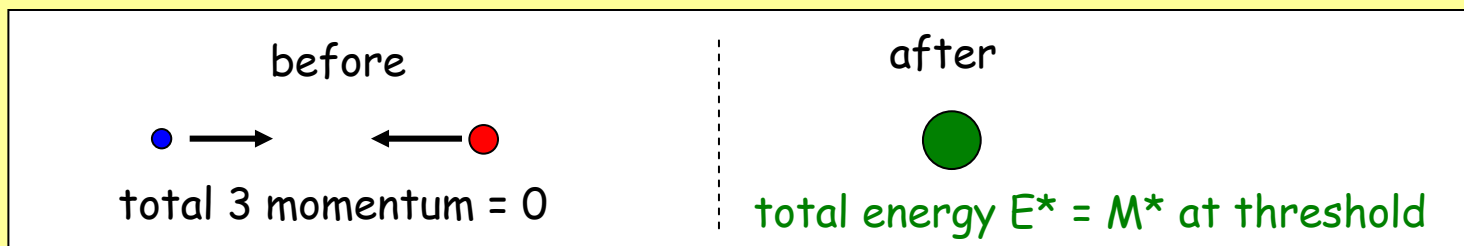
write down total 4-momentum in both lab and CM frames:

lab: $P_\mu = (\vec{p}, i(E + M))$ CM: $P'_\mu = (0, iE*)$

lab   CMS   TRICK: length^2 of a 4 vector is invariant!!!

$$P^2 = (P')^2$$

$$\Rightarrow \ p^2 - (E+M)^2 = -(E^*)^2$$

$$for \ \ m_{beam} << E \ \ ie \ \ relativistic \ beam, (approx.) \ then$$

$$\Rightarrow \ E^* = \sqrt{2ME + M^2}$$

Available energy to make new particles goes up as the square root of the beam energy

Now consider a colliding beam experiment – for simplicity, take equal mass particles eg. e+ and e- as used at the LEP collider at CERN. Then the LAB frame and the CM frame are the same!

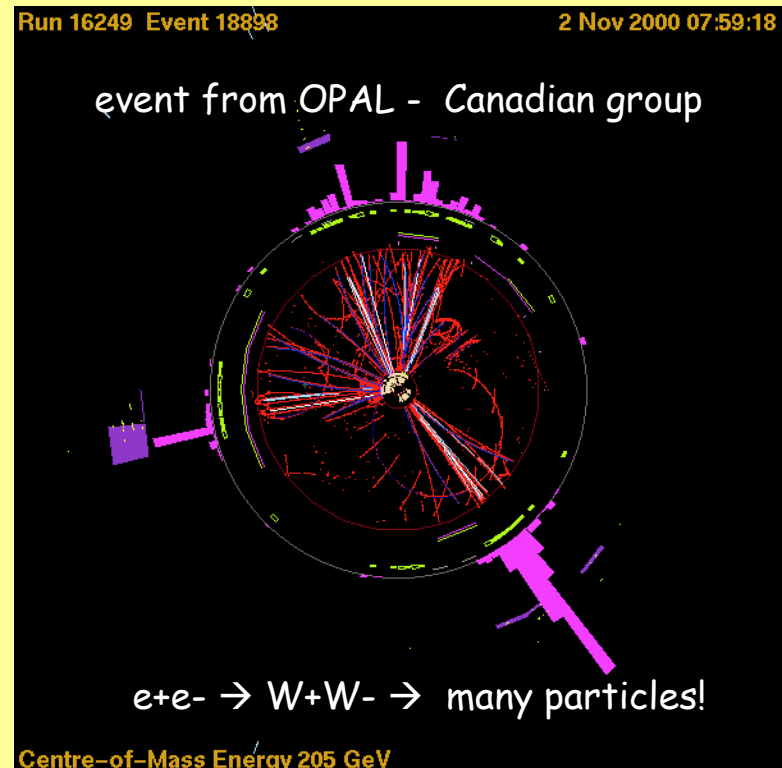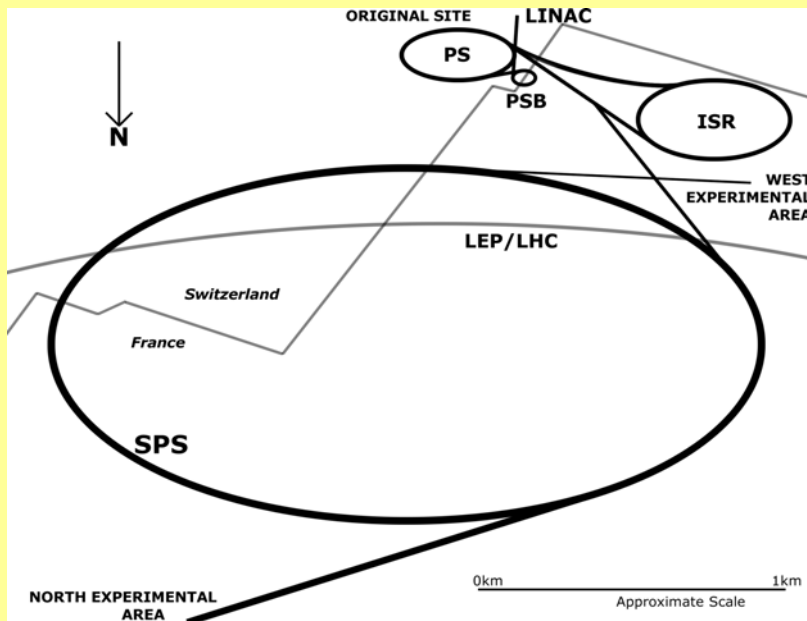E_1 before   after

                              E_2

total 3 momentum = 0   total energy $E^* = E_1 + E_2 = 2E_1$
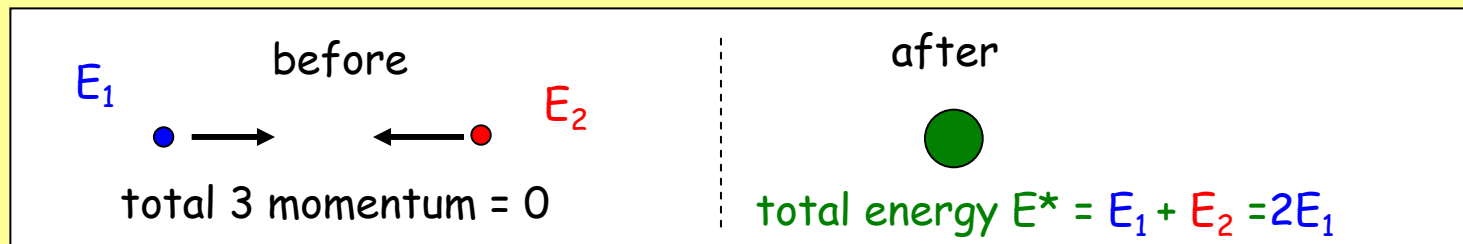
Available energy to make new particles goes up linearly with beam energy → more efficient!

several international collaborations built sensitive "calorimeter" and tracking detectors to record final state particles produced in high energy e+ e- collsions to search for new particles at LEP (now decommissioned to be replaced by the LHC or "Large Hadron Collider")

ORIGINAL SITE   LINAC
PS
PSB
ISR
WEST EXPERIMENTAL AREA
LEP/LHC
Switzerland
France
SPS
NORTH EXPERIMENTAL AREA
N
0km   1km
Approximate Scale

Run 16249 Event 18898   2 Nov 2000 07:59:18

event from OPAL - Canadian group

e+e- → W+W- → many particles!

Centre-of-Mass Energy 205 GeV

Particle Data Group: cross section for e+e- annihilation at high energy

- resonance peaks for production of neutral particles – meson resonances seen at lower energy.   All of these have J = 1, negative parity (recall pion has J = 0)
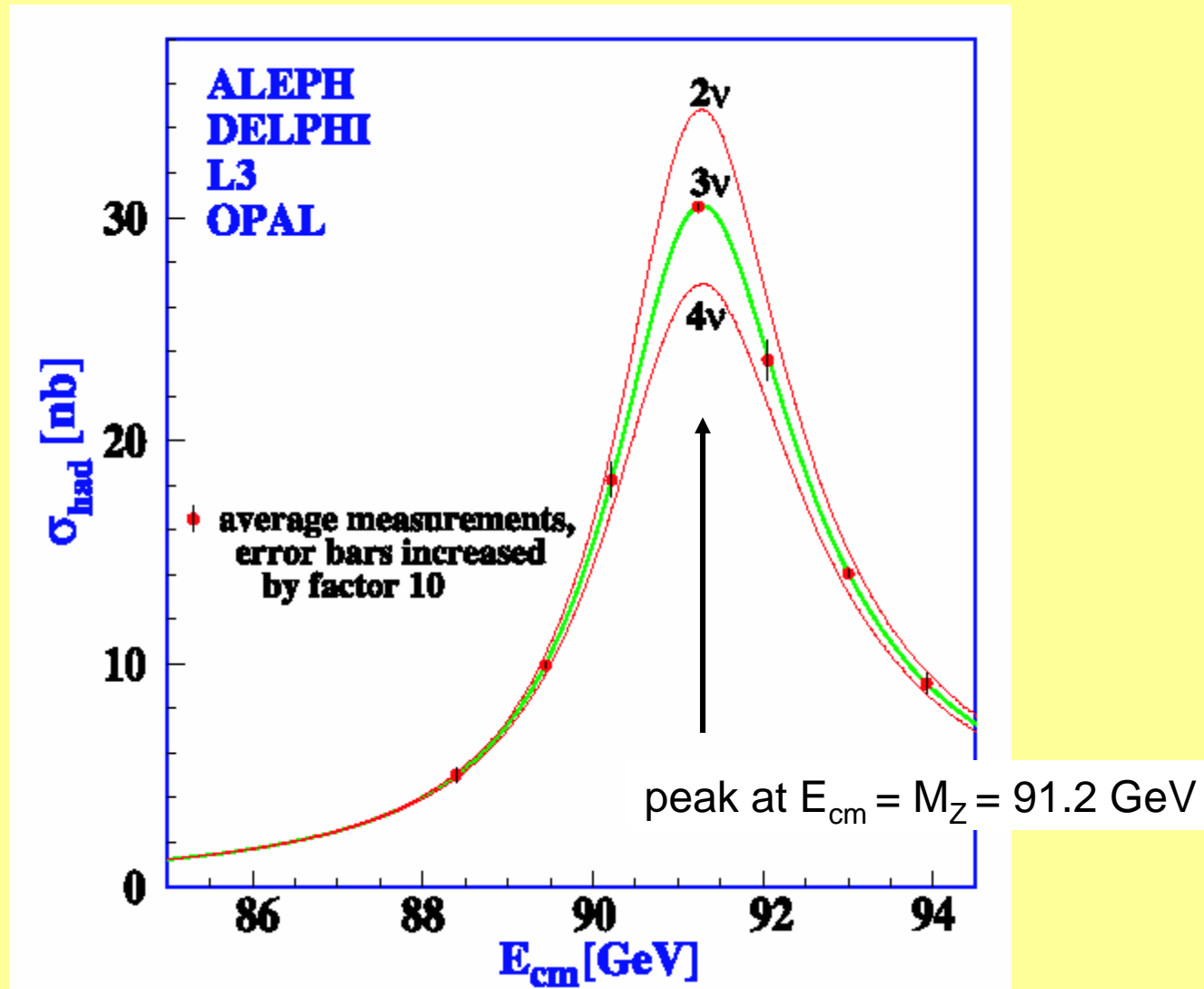
$$\rho = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \quad T = 1 \qquad \omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}), \ T = 0$$

$$\phi = s\bar{s} \qquad J/\psi = c\bar{c} \qquad \Upsilon = b\bar{b}$$

Z boson, discovered 1983, CERN
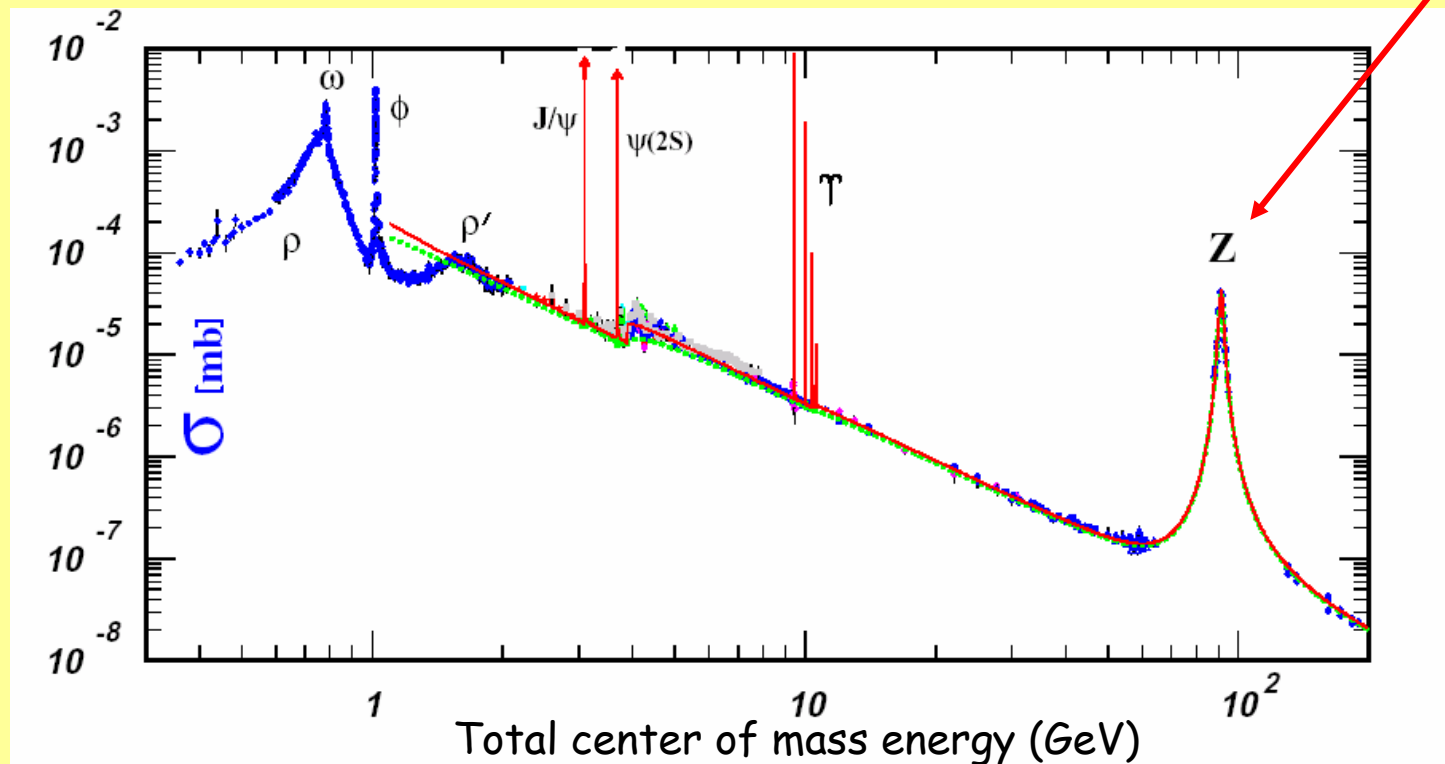
peak at $E_{cm} = M_Z = 91.2$ GeV

(N = 3 looks pretty good!)

Fit gives N = 2.994 +/- 0.012 neutrino types!

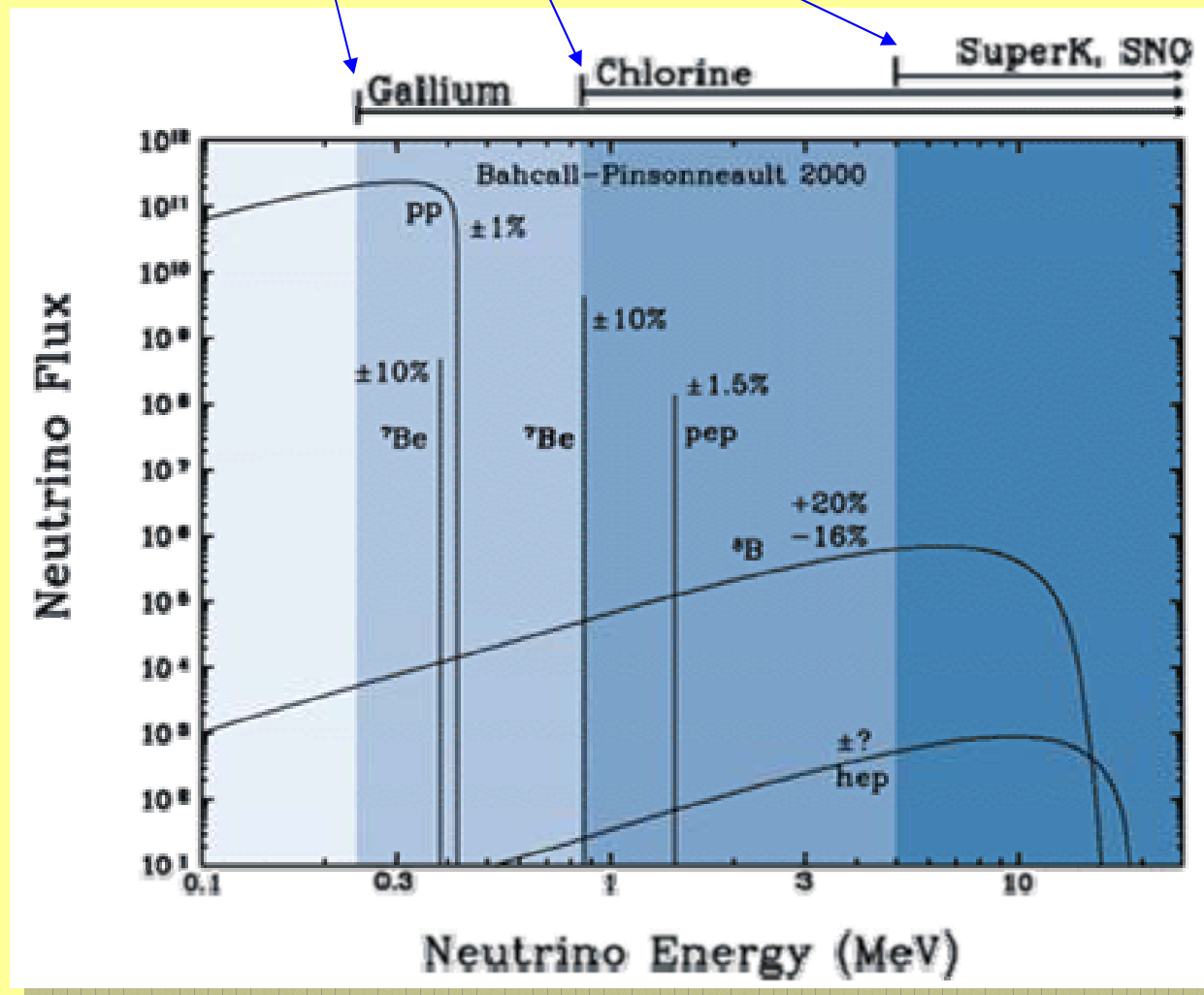Sudbury Neutrino Observatory: http://www.sno.phy.queensu.ca/
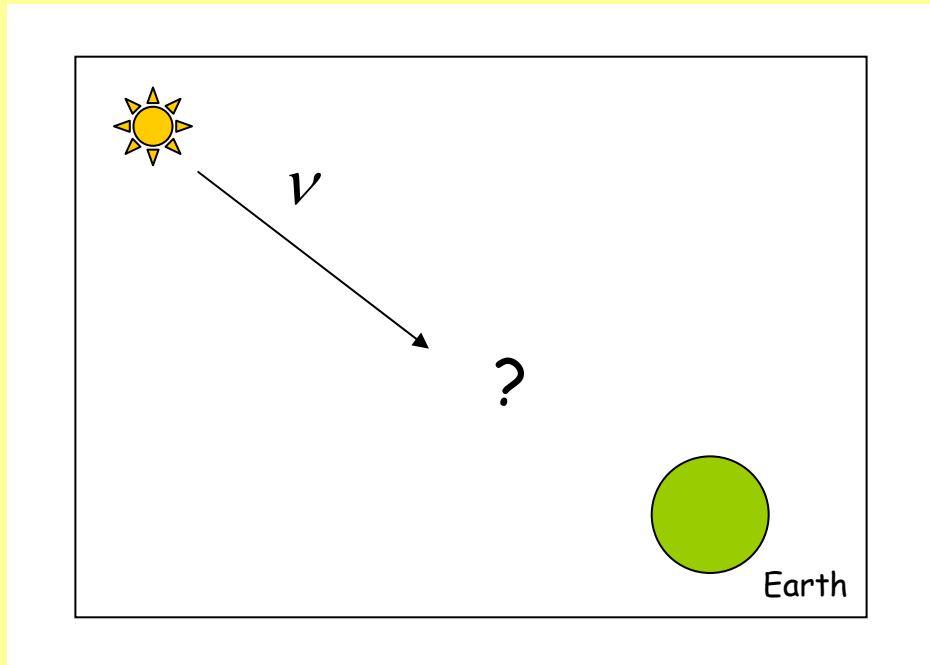
- SNO was built over a decade starting in the late 1980's at a cost of ~ $100M to solve a long-standing problem in the observed deficit of neutrinos coming from the sun.

- A classic radiochemical experiment by Ray Davis et al carried out in a gold mine in South Dakota using the reaction:

$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$$
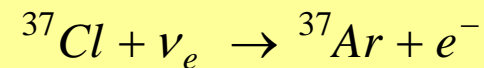
had reproducibly detected only about 1/3 of the expected number of neutrinos of solar origin. What was wrong???

Prior to SNO, several other solar neutrino experiments were constructed and in operation world wide, e.g. the Kamiokande detector in Japan, SAGE and GALLEX detectors in Europe ... all had slightly different energy sensitivities and operated using different reactions to detect the neutrinos, but all found a discrepancy in the solar flux!
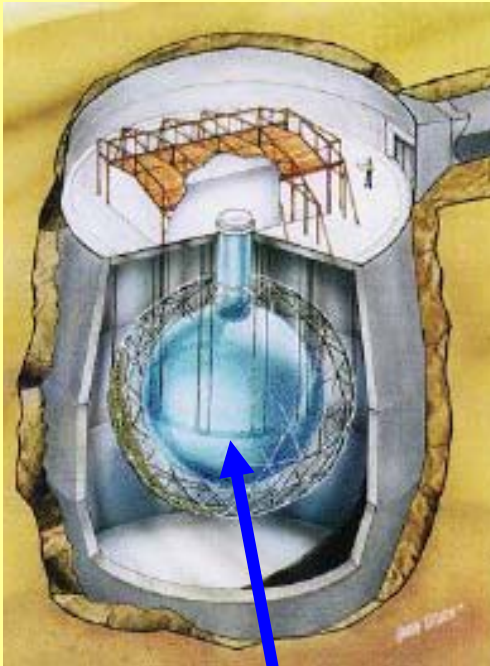
Energy thresholds of various detectors are shown:

Ref: Williams, section 14.7

Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000
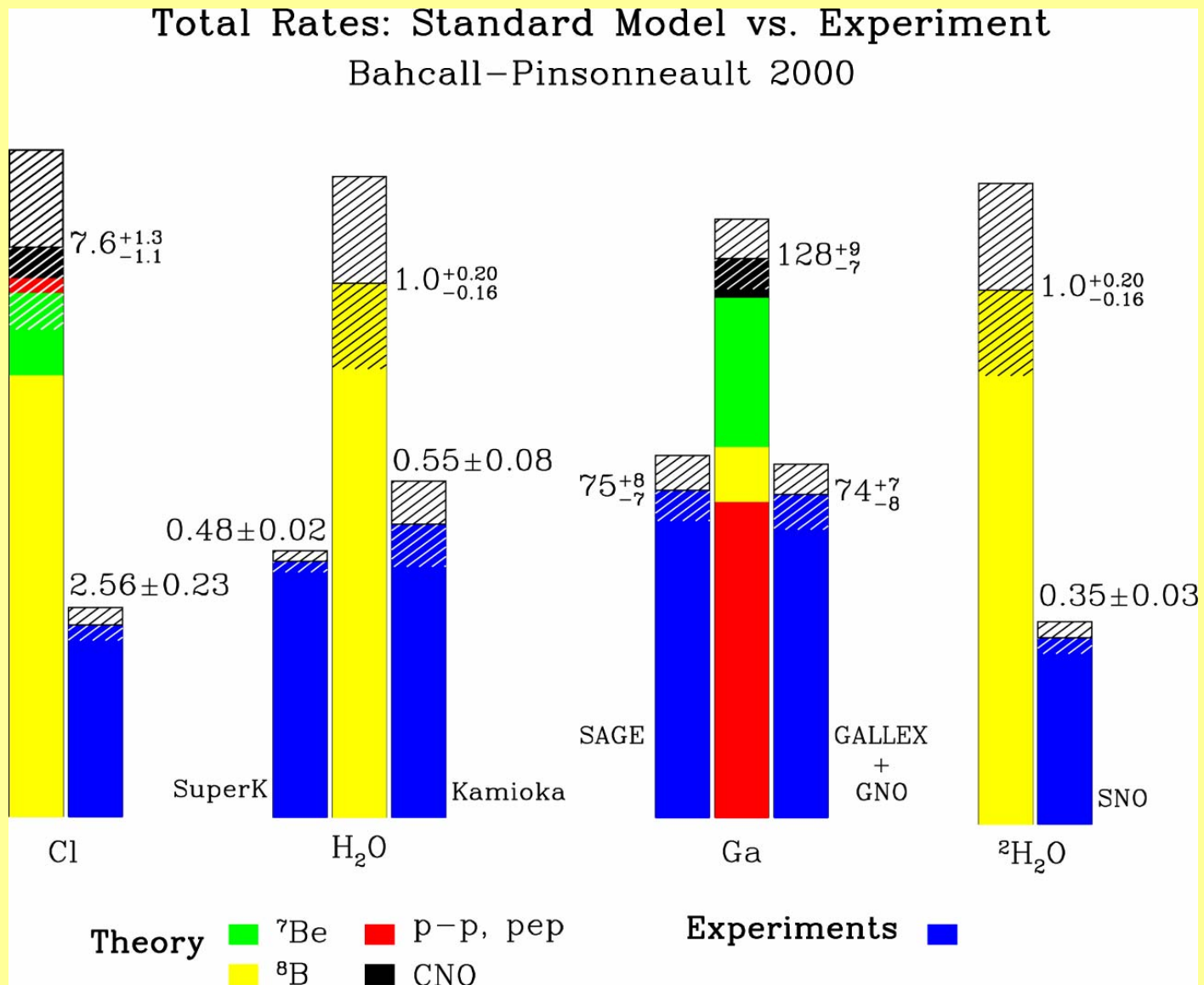
# SNO – a unique D_2O Cerenkov detector that can "see" all neutrino types

4700' underground in the Creighton nickel mine in Sudbury, Canada, to suppress background from cosmic ray muons, etc:

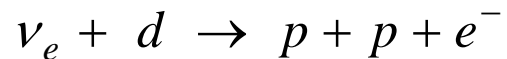acrylic vessel holds 1000 tonnes of heavy water, D_2O that makes an ideal detector for neutrinos.

20" diameter photo-multiplier tubes looking inward detect Cerenkov light when a neutrino interacts in the water
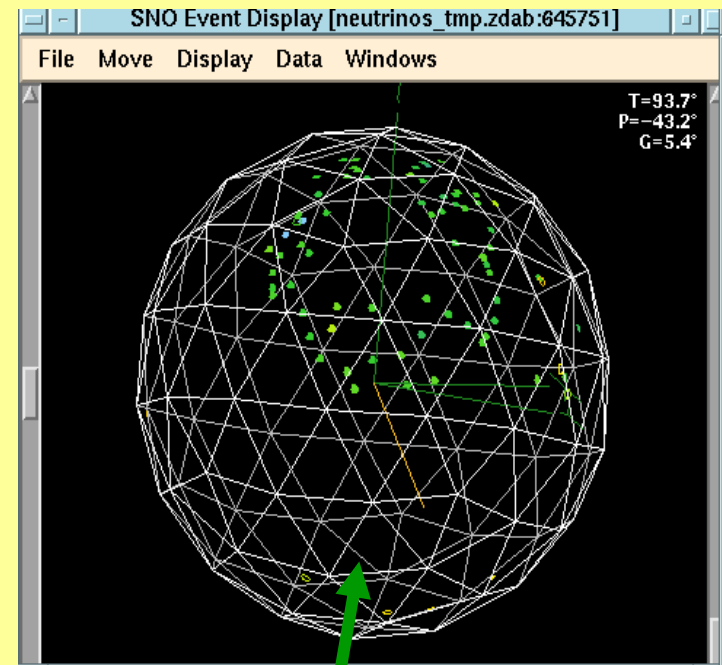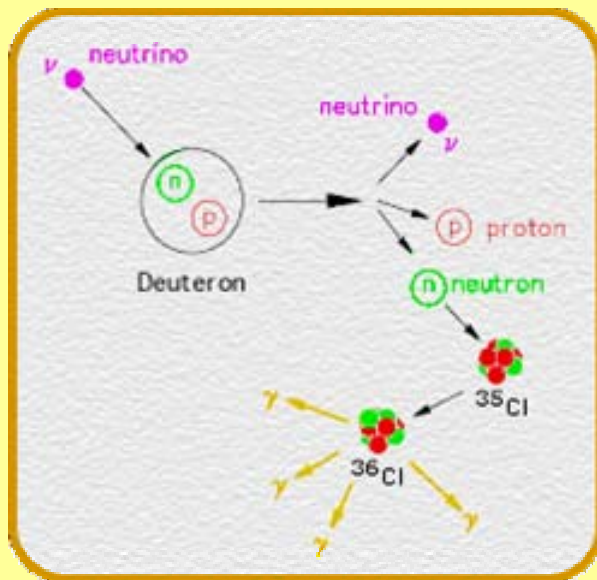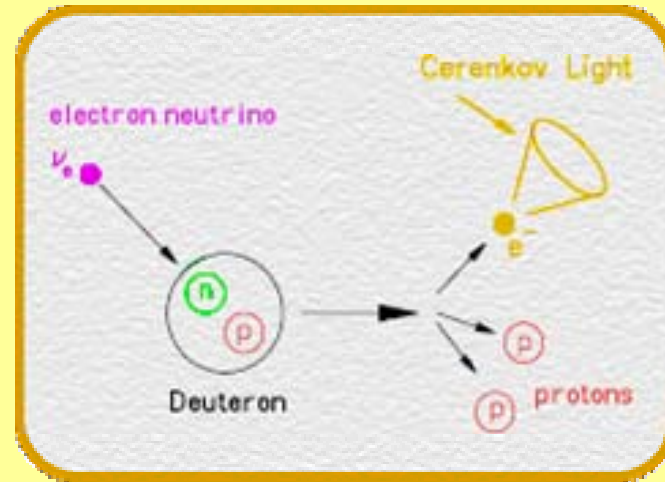
Neutrino candidate event: Cerenkov "ring" on one side of the detector with nothing entering from the other side.

1. "Charged current" mechanism:

$$\nu_e + d \rightarrow p + p + e^-$$

(electron produces Cerenkov light in the water tank)

Cerenkov Light

electron neutrino

ν_e

n

p

Deuteron

e

p

p protons

neutrino

ν

neutrino

ν

n

p

Deuteron

p proton

n neutron

^{35}Cl

^{36}Cl

2. "Neutral current" mechanism:

$$\nu + d \rightarrow n + p + \nu$$
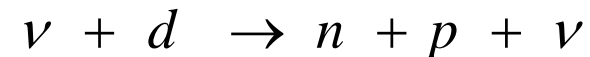
resulting neutron can be captured in a salt solution, and resulting γ-rays, which hit electrons in the water, again produce Cerenkov light that is picked up in the PMT's

Ratio of 1 : 2 gives the ratio of electron-type to total neutrinos from the sun!

$$\Phi_{CC} = 1.76 \pm 0.05 \pm 0.09 \cdot 10^6 \, \text{cm}^{-2} \, \text{sec}^{-1}$$

electron-neutrinos only

$$\Phi_{NC} = 5.09 \, ^{+0.44}_{-0.43} \, ^{+0.46}_{-0.43} \cdot 10^6 \, \text{cm}^{-2} \, \text{sec}^{-1}$$

all neutrino types

Ratio:

$$\frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} = 0.35$$

Significance of the SNO result: first experiment to "see what happened" by measuring all neutrino types

Interpretation:
- the total number of neutrinos is consistent with expectations from the solar model.
- only electron-type neutrinos are produced in solar fusion reactions
- 2/3 of these must be turning into other neutrino types (μ, τ) before reaching earth!
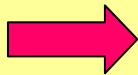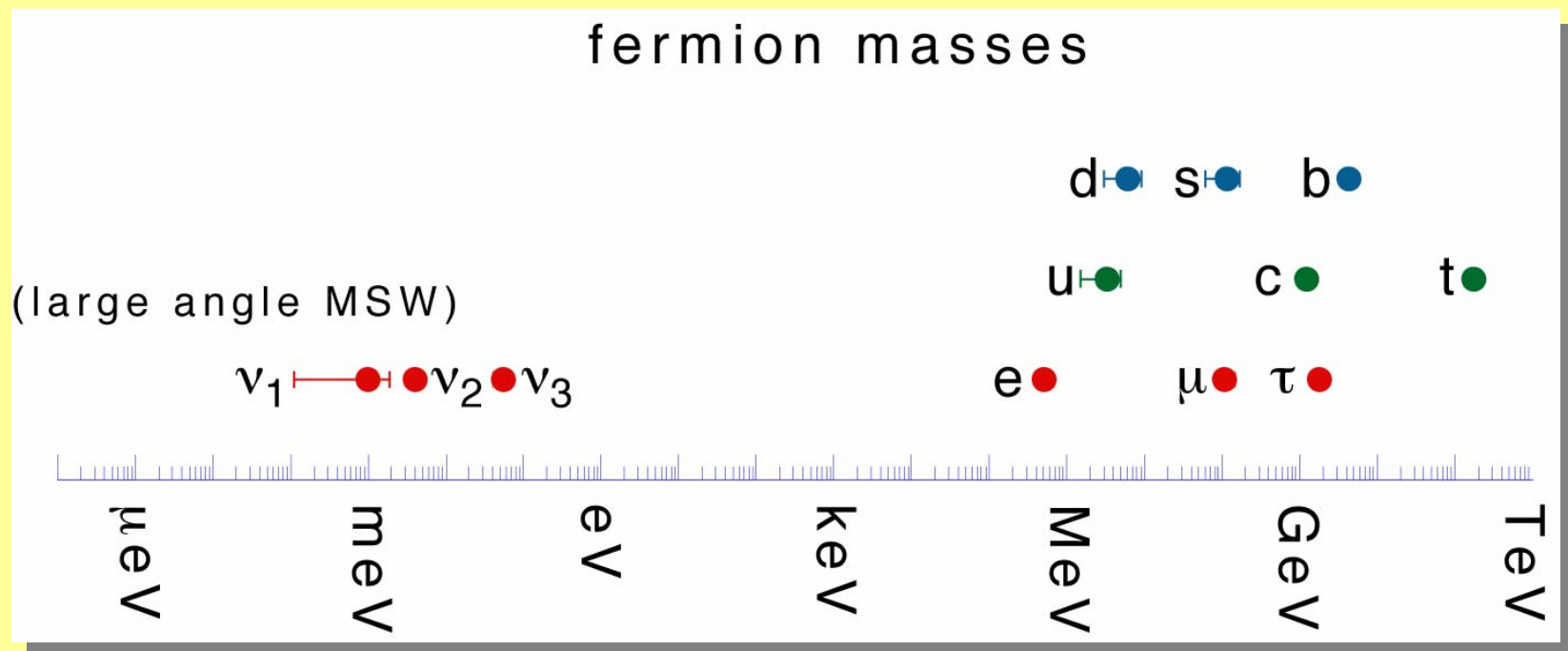
Unavoidable conclusion: neutrinos must have a small but finite rest mass! (next question: how big is it?)

The theory of neutrino mixing gets complicated very quickly, but in a nutshell,
the observation of "neutrino oscillations" sets limits on the mass-difference Δm^2
and the mixing angle θ, e.g. for only two neutrino types, one could write:

$$\left| v_e(t=0) \right\rangle \;=\; \sin\theta \left| v_1 \right\rangle + \cos\theta \left| v_2 \right\rangle$$

Then as time evolves, with the masses of 1 and 2 being different, the observed
"neutrino state" will be a different linear combination of 1 and 2 that depends on
the parameters Δm^2 and $\sin^2\theta$. Combined data from all experiments can be used to place
limits on the mixing parameters.... so far, the favoured situation looks like this:

fermion masses

(large angle MSW)

d s b

u   c   t

v_1 — v_2 v_3

e μ τ

meV   meV   eV   keV   MeV   GeV   TeV

http://www.nserc.ca/news/2003/p031124.htm

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Leader of Sudbury Neutrino Observatory Wins Top Canadian Science Prize

Ottawa, Ontario, November 24, 2003 – Arthur McDonald was today named winner of the 2003 Gerhard Herzberg Canada Gold Medal for Science and Engineering.

The prize guarantees that Dr. McDonald, a professor at Queen's University, will receive $1 million in research funding from the Natural Sciences and Engineering Research Council (NSERC).

"Dr. McDonald was the driving force for the Sudbury Neutrino Project, which has been such an outstanding international scientific success story and a source of great pride for all Canadians," said Ottawa-Vanier M.P. Mauril Bélanger, who announced the award on behalf of

It wasn't easy! For a few years, the subatomic research community almost went broke trying to pay for SNO .... but it was worth it!

SAP visits SNO as chair of NSERC GSC, 1997 – borrows $3M from NSERC to pay for construction cost overrun....